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DEVELOPMENT AND EVALUATION OF DILUTION PROBES USED FOR SAMPLING TO DETERMINE SOURCE SIGNATURES

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ABSTRACT

The NEA, Inc., stack sampling system was evaluated. It is designed for obtaining emission-source samples in two particle-size ranges (<2.5 μm and 2.5-10 μm) corresponding to those covered by dichotomous atmospheric samplers. The stack gas sample is continuously drawn through a nozzle and probe, and is diluted with a measured flow of filtered air. A fraction of the diluted sample is drawn through collection filters in a dichotomous sampler. Laboratory tests of the equipment were made in a wind tunnel 10 cm in diameter, using monodisperse ammonium fluorescein aerosol particles 1.3-16 μm in diameter generated by a spinning disk. The system was judged to be reasonably well suited for defining emission source signatures. However, high losses of the larger particles due to inertial effects at the nozzle and deposition of particles in the probe and connecting plastic hose resulted in biased particle-size distributions at the filters. The losses could be partially compensated for by reducing the length of the hose, using a right angle precollector with a larger cutoff diameter (12.5 μm), and by controlled anisokinetic sampling to oversample the larger particles. The loss of electrically-charged particles was 4 times that of charge-neutralized particles.

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INTRODUCTION

Source apportionment studies based on chemical element balance techniques require elemental composition signatures for the sources involved.[1,2] Ideally, the same, or similar, sampling methodologies would be used in obtaining source samples as those used in obtaining samples from the ambient air. NEA, Inc., designed a sampler for this purpose which uses a slightly modified ambient air "dichotomous sampler" to provide source samples in two size fractions (0-2.5 μm and 2.5-10 μm) corresponding to those taken in the ambient air.[3] The samples are obtained on the filter media used for ambient sampling. The NEA system is illustrated in Figure 1. In operation, a sample is withdrawn continuously from the stack (source) via the nozzle (1) and probe (2) and conveyed via the flexible hose (3) to a dilution device (4). In the dilution device the sample stream is diluted by mixing with a measured flow of filtered ambient air provided by the blower and filter (5). A portion of the diluted stream is withdrawn via the inlet tube (6) to the dichotomous sampler (7).

This system has two major advantages over conventional sampling methods for obtaining source signatures. First, the sample is obtained with the same particle-size fractionation method that is used in many ambient air receptor studies; and second, the dilution process mimics to some extent the processes which take place as the flue gases are discharged to the atmosphere, including condensation of certain species which may be in the vapor phase at stack conditions. The time available for such condensation processes in the NEA system is, however, rather short (one to two seconds) and consequently the mixing occurs more rapidly than in the "real world". As a result of the short mixing time, the final aerosol properties may not be quite those of the actual plume. Nonetheless, samples obtained with the dilution system are probably more similar with respect to condensible components to those downwind in the plume than samples taken at flue gas conditions.

The problem of most concern with regard to samples obtained with the NEA system is the possibility of size-dependent particle losses in its various components. Losses could bias the size distribution of the samples obtained, and, if the elemental composition of the particles emitted by a source was strongly size dependent, the source signature derived from the sample might not be valid. Southern Research Institute was asked to: (1) evaluate the representativeness of samples taken using the NEA system with

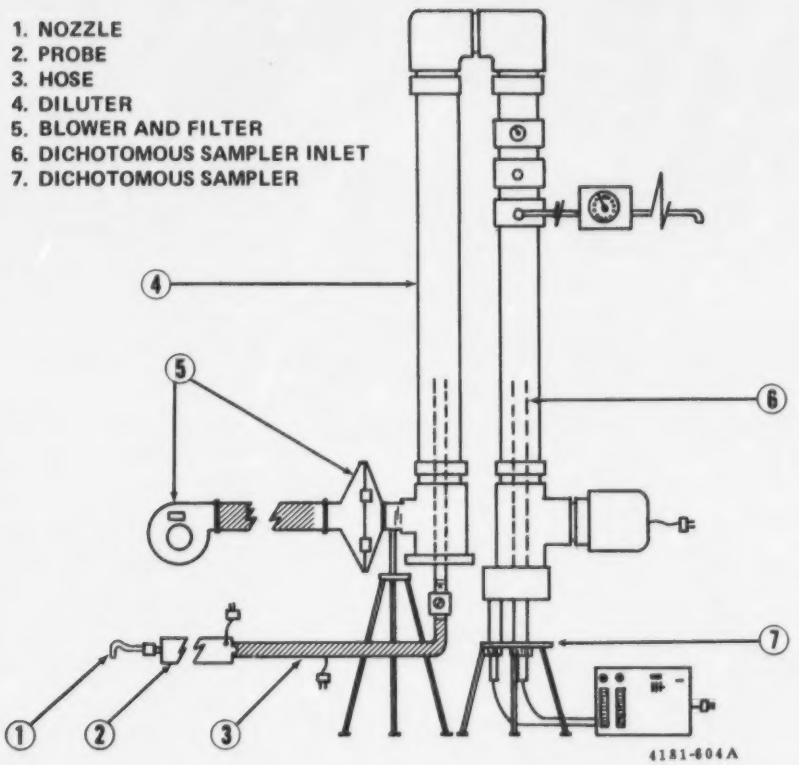

Figure 1. NEA Dilution Sampling System.

regard to particle-size bias and (2) if such biases were a problem, rectify them insofar as possible, or (3) suggest alternative procedures for obtaining representative samples.

CONCLUSIONS AND RECOMMENDATIONS

Two laboratory calibration studies of the system were performed which revealed (1) substantial losses of large particles owing to inertial effects, and (2) other particle-size-dependent losses which resulted from electrostatic charge effects.

These losses would introduce serious biases in the particle-size distribution of samples obtained with the system. Mechanical modifications were made which, together with a reduction in sample flow rate, reduced the losses substantially--but the reduction in losses was not sufficient for truly satisfactory field application. However, compensation for mechanical losses was found to be possible through oversampling of the larger particles at the probe inlet. This compensation can be achieved by sampling anisokinetically using an oversize inlet nozzle.

Reproducibility of the flow-pressure drop characteristics of the probe and hose was found to be poor. The use of this pressure drop for setting the sample flow does not appear to be accurate or reproducible. This is particularly true in light of our experience with a damaged hose. Even in the absence of permanent damage, minor distortions and kinks in the hose can result in significant flow errors. Therefore it is recommended that a venturi-type flow meter be installed at the probe exit or diluter inlet so that a more reproducible and certain flow measurement can be made. Thermostatic control of the hose heater is also recommended so as to avoid overheating problems to which the hose supplied us by NEA had been subjected.

The problem of electrostatic losses in the hose and diluter can be serious, and no solution can be suggested at present. Charged particles can be expected to be present in the exhausts of electrostatic precipitators; it has also been noted that very high, unipolar, charges can be present on particles in the exhaust of a boiler, upstream of any control device.[4] Strong, size-dependent, biases in the samples obtained using the apparatus are possible. The data do suggest that the electrostatic deposition problems may largely be avoided if only conducting components are used throughout the system.

The diluter inlet pipe to which the hose is connected has no provision for heating. If condensibles are to be properly handled by the system, this pipe should be heated in order to avoid losses by condensation on the walls of the pipe.

Except for the problems arising from electrostatic charge effects, and the possible problems related to the retention of some types of particles by the filters, the system appears to provide a reasonable method for collecting samples for defining source signatures.

SYSTEM OPERATION

In field operations the system is set up at the sampling location and the velocity at the selected sampling point is measured. A nozzle and sampling rate are selected for isokinetic sampling and a total flow of sample plus dilution air is selected to obtain the desired dilution factor. The probe and hose are brought to operating temperatures by means of permanently wrapped heating tapes and the dichotomous sampler is loaded with a pair of filters. The probe is then inserted into the stack and sampling is begun. The sample flow is set and monitored by means of the pressure drop from the nozzle tip to the interior of the diluter--laboratory calibrations being used to establish the relationship between the pressure differential and the sampling flow rate. (The pressure differential used must include the velocity pressure of the gas stream at the sampling point.) The sampling rates and the total flow through the diluter are adjusted by varying the fan speeds of the dilution air inlet blower and the exhaust air blower. The total flow (sample plus dilution air) is measured by means of a thermal anemometer located in the second half of the main body of the diluter.

EXPERIMENTAL METHODOLOGY

System losses by particle size were examined over the range from 1.5 to 16 μm by challenging the system in a series of tests with monodisperse particles generated using a spinning disk aerosol generator. The particles were introduced to the system by sampling from a small (10 cm) diameter wind tunnel into which the probe end and sampling nozzle could be introduced. The gas velocities in the tunnel ranged from 5 to 20 m/s, spanning the range commonly encountered in actual field conditions. The test particles were made of ammonium fluorescein, which forms dry, relatively hard, non-hygroscopic particles. System losses were determined by breaking the system down into its component pieces and washing each internal surface with dilute ammonium hydroxide. The amounts of fluorescein in the washes were then measured by fluorimetry. In order to be able to account for all the aerosol sampled, a modified hi-volume filter assembly was used at the exhaust end of the system in addition to the blower as shown in Figure 1. Washes of this filter together with those from the system itself made a complete mass balance possible.

Investigation of electrostatic effects in the sampling system was not planned as a part of the program; however, a charge neutralizer in the aerosol generator failed after much of the testing had been completed, resulting in dramatic increases in the losses (and much frustration in identifying the cause of the sudden increase in losses over those which had previously been measured). A total of 16 calibration tests were made with the complete system with neutral aerosols, 14 tests were made with the complete system with charged particles, and an additional 11 tests were made with the nozzle, probe and hose only, to further characterize the electrostatic effects and look into the effectiveness of inlet charge neutralizers for alleviating the electrostatic losses.

RESULTS OF THE EXPERIMENTS

TESTS WITH NEUTRAL PARTICLES

The results of the first series of tests, those involving the full system and neutral particles, are summarized in Tables 1-3 and Figures 2, 3, and 4. In this series of tests, particles ranging in size from 1.3 to 16 μm were used with sampling rates of 14 and 76 l/min and gas velocities from 8 to 17 m/s. A second, isokinetic, sampler, consisting simply of a nozzle and filter assembly, was operated in parallel with the NEA system to provide reference values of the true concentrations of the test aerosols for comparisons with concentrations derived from the dichotomous sampler filters.

Very low losses were measured on surfaces within the diluter proper during this series (e.g. 0.7% at 10μm particle size, and similar, negligible losses for the other sizes used). However, losses in the nozzle, probe, and hose were unacceptably large when the system was operated under the initial protocol specified by NEA. The protocol called for very high sampling rates (approx. 75 l/min) and a 3-m hose to permit as much flexibility as possible in setting the equipment up in the (usually cramped) sampling areas found at industrial sites. Under these conditions, losses in the hose alone ranged from 45% at 2 μm to 99% at 15 μm, as shown in Figure 2. At 76 l/min sample flow, the Reynolds number of the flow in the hose and probe was approximately 8000, indicating that the flow would be turbulent. Because particle losses are expected to be greater under conditions of turbulent flow than in laminar flow, the sample flow was reduced to 14 l/min. At this sampling rate the Reynolds number was reduced to about 1500.

One test was made at the reduced flow using 7 μm particles as the aerosol. Some reduction in the losses was obtained compared to the 75 l/min value, as is also shown in Figure 2. However, the reduction was not great enough to make the system useful for particle sizes larger than about 3 to 5 μm, while satisfactory

Table 1. Calibration Test Parameters for First Test Series (Neutral Particles)

Test	Particle Diameter, μm aerodynamic	Duct Velocity, m/s	Nozzle Size, in., and Type[a]	NEA Sample Flow Rate, lpm	Dilution Chamber Velocity, m/s	Comments
			------10-ft Hose------			
1	10.4	10	1/2 GN	76	2.3	Reynolds No. ~8000 in probe and hose (Tests 1-6)
2	7.0	10	1/2 GN	76	2.3	
3	7.0	10	1/2 GN	76	2.3	
4	16.3	10	1/2 GN	76	2.3	
5	4.5	10	1/2 GN	76	2.3	
6	2.5	10	1/2 GN	76	2.3	
7	7.8	7.5	1/4 GN	14	1.2	
			-------5-ft Hose-------			
8	7.8	7.5	1/4 SRRA	14	1.2	Reynolds No. ~1500 in probe and hose (Tests 7-16)
9	4.5	7.5	1/4 SRRA	14	1.2	
10	7.8	7.5	1/4 SRRA	14	1.2	
11	1.3	7.5	1/4 SRRA	14	1.2	
12	2.3	7.5	1/4 SRRA	14	1.2	
13	9.3	16.5	3/8 FSRA	14	1.2	Anisokinetic to boost large particle concentration entering dichotomous sampler (Tests 13-16)
14	8.4	16.5	3/8 FSRA	14	1.2	
15	9.7	15	5/16FSRA	14	1.2	
16	9.7	15	5/16FSRA	14	1.2	

[a]GN = gooseneck; SRRA = Southern Research prototype right angle precollector; FSRA = Flow Sensor (commercial) right angle precollector.

Table 2. Raw Concentration Data from First Test Series

Test	Particle Diameter, μm aero-dynamic	Particle Concentrations, arbitrary units			
		Reference[a]	NEA, Total	NEA BUF[b]	NEA Dichotomous[c]
		-----10-ft Hose-----			
1	10.4	--	106.8	6.6	6.1
2	7.0	--	38.9	6.2	8.5
3	7.0	73<C<91	86.4	11.6	13.0
4	16.3	(3.5)	9.5	0.050	--
5	4.5	71.9	75.7	23.6	27.8
6	2.5	10.9	11.6	5.9	9.0
7	7.8	139.0	128.0	28.5	--
		------5-ft Hose------			
8	7.8	174.0	197.0	95.9	103.0
9	4.5	80.9	65.4	47.4	60.0
10	7.8	438.0	617.0	293.0	750.0
11	1.3	2.49	2.67	2.46	1.9<C<3.0
12	2.3	46.8	44.2	41.6	48.8
13	9.3	19.4	64.9	28.4	--
14	8.4	53.3	158.0	77.6	93.4
15	9.7	53.6	138.0	30.8	35.2
16	9.7	67.0	136.0	64.7	52.6

[a]Particles collected with an isokinetic sampler consisting of a nozzle and filter.
[b]Backup filter - total flow of hi-vol filter at dilution system exhaust.
[c]Total concentration measured by dichotomous sampler.

Table 3. Normalized Calibration Data for NEA Train in First Test Series

Test	Particle Diameter, μm, aerodynamic	Concentration Ratios					
		Calculated[a] NEA/Reference	Measured NEA/Reference	NEA BUF/ Reference	NEA Dichotomous/ Reference	NEA BUF/ NEA Total	NEA Dichotomous/ NEA Total
		———10-ft Hose———					
1	10.4	1.00	--	--	--	0.061	0.057
2	7.0	1.00	--	--	--	0.156	0.22
3	7.0	1.00	0.945-1.18	~0.14	0.15	0.133	0.15
4	16.3	1.00	~2.75	~0.014	--	0.005	--
5	4.5	1.00	1.05	0.33	0.39	0.31	0.37
6	2.5	1.00	1.06	0.54	0.83	0.50	0.78
7	7.8	1.00	0.92	0.20	--	0.22	--
		———5-ft Hose———					
8	7.8	1.00	1.13	0.55	0.59	0.48	0.52
9	4.5	1.00	0.81	0.59	0.74	0.72	0.92
10	7.8	1.00	1.41	0.67	1.71	0.48	1.22
11	1.3	1.00	1.07	0.99	0.76-1.2	0.91	0.71-1.12
12	2.3	1.00	0.94	0.89	1.04	0.93	1.10
13	9.3	3.03	3.35	1.46	--	0.43	--
14	8.4	2.82	2.96	1.46	1.75	0.49	0.59
15	9.7	2.20	2.57	0.58	0.66	0.22	0.26
16	9.7	2.20	2.04	0.97	0.78	0.46	0.38

[a]Calculated enhancement of NEA concentration for anisokinetic sampling conditions used.

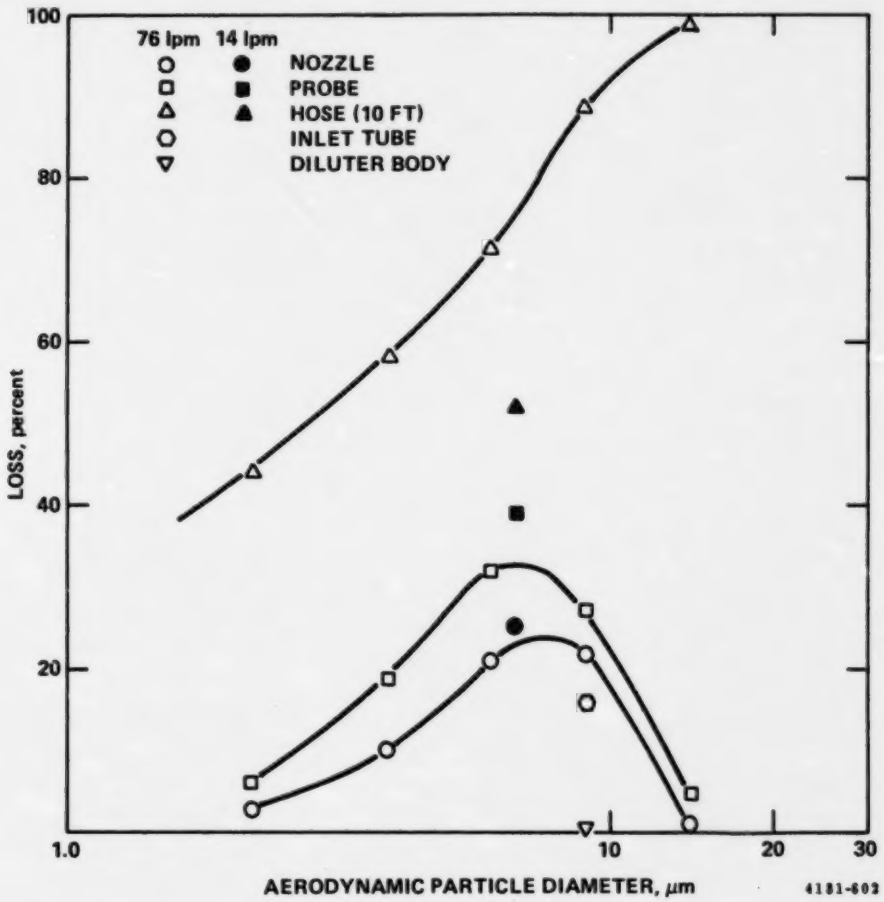

Figure 2. Percentage loss by particle size for system components at sampling flow rates of 76 and 14 lpm using 10-ft hose.

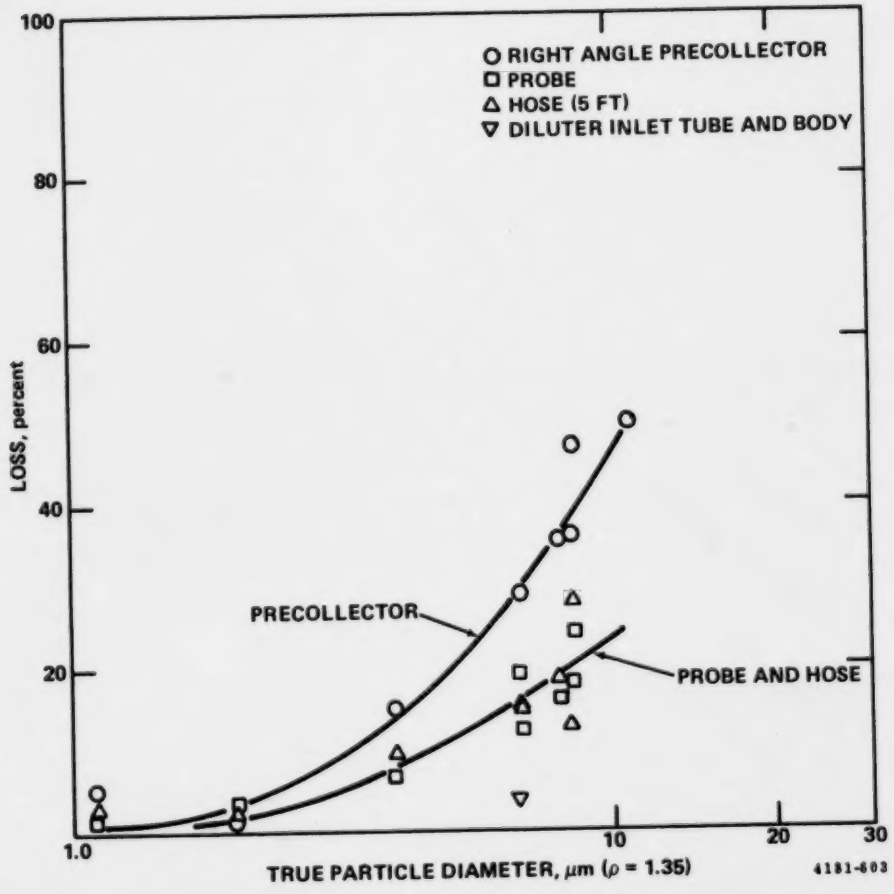

Figure 3. Precentage loss by particle size for system components at a flow rate of 14 lpm using 5-ft hose.

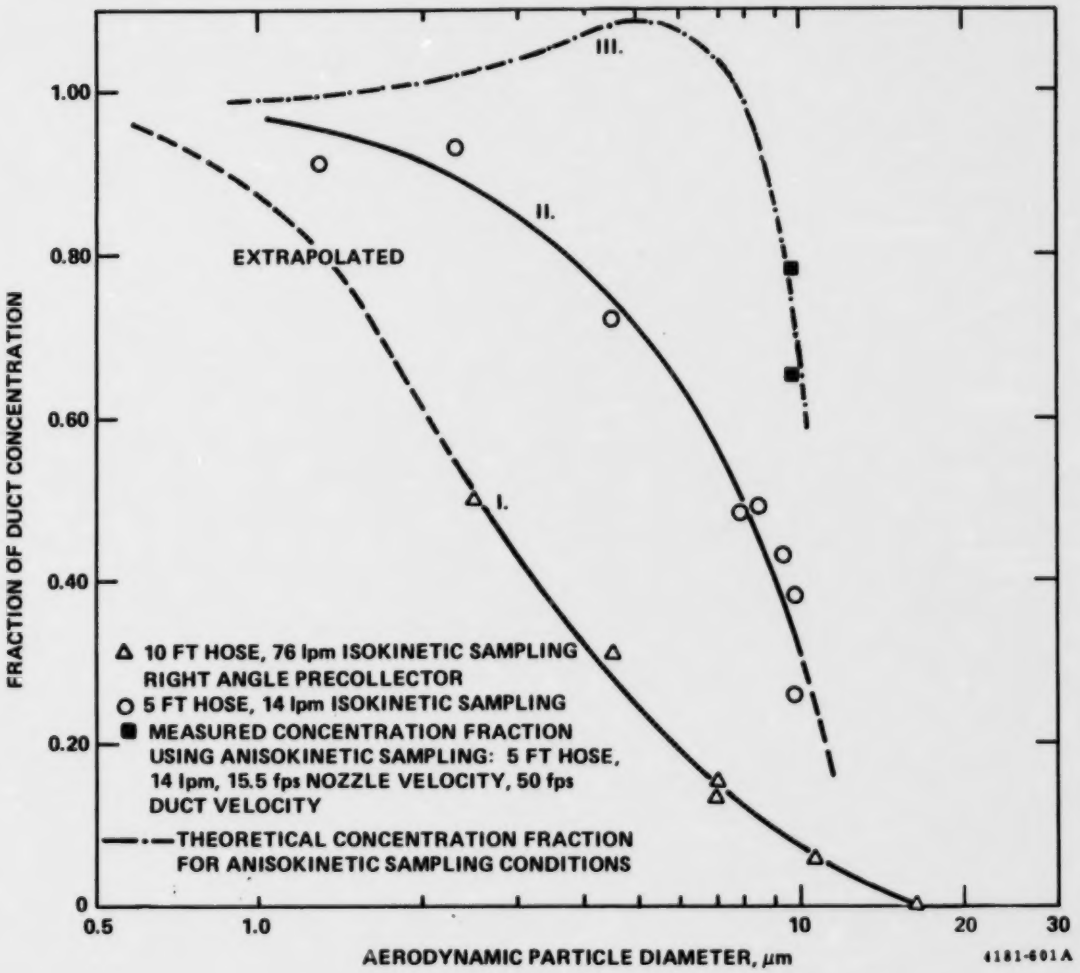

Figure 4. Fraction of duct concentration, corrected for dilution, at dichotomous sampler inlet vs. particle size.

operation up to 10-15 μm was needed to support the "Inhalable Particulate" program. The nozzle losses remained about the same as on the previous 75 l/min runs, the probe losses increased somewhat (probably from increased settling at the lower flow), and the losses in the hose declined significantly. However, losses in the hose were still unacceptably large.

Although the flow rate had been reduced, losses in the nozzle were still high, and for gas streams having velocities in the range of 20 to 40 m/s, which are commonly encountered in industrial gas streams, even larger nozzle losses would be expected.[5,6] As an example, the particle cutoff diameter (D_{50}) of a 4.75 mm gooseneck nozzle sampling at isokinetic rates from a 40 m/s gas stream is about 1.5 μm. A right angle precollector, developed at Southern Research[7] to minimize nozzle losses in sampling with cascade impactors, produces a moderately sharp, predictable particle cutoff diameter in the range of 10 to 15 μm at a sampling rate of 14 l/min. Thus the use of the precollector would reduce particle losses at the entry to the probe to acceptable levels under almost any sampling circumstances envisioned for the use of this system. For the conditions at which the evaluation was made, the precollector D_{50} was estimated to be 12.5 μm on an aerodynamic basis. During the remainder of the evaluation, the gooseneck nozzles were replaced with this precollector.

In order to further reduce the losses in the hose, a second hose with a slightly larger bore and a length of 5 ft was substituted for the original (both were of the same nominal bore size and were made by the same manufacturer). Particle losses by diameter in the precollector, probe, and hose when operated with the revised setup and flow rate are shown in Figure 3. By reducing both the sampling flow rate to 14 l/min. and the length of the hose to 5 ft, the losses approached acceptable levels, as illustrated in Figure 3. However, samples obtained in this fashion would have still been significantly depleted in the 5 to 10 μm interval.

The net penetration, by particle size, to the plane of the inlet of the dichotomous sampler is shown in Figure 4 for each of the test conditions and protocols previously described. By using the shorter hose, lower sampling rate, and the precollector, the overall system penetration was improved from the lower curve (I) shown in Figure 4 to the levels shown by the middle curve (II). However, a large bias still existed for particles in the upper end of the size range to be covered, with losses approaching 70% at a diameter of 10 μm. At this point it appeared unlikely that any further significant reductions in the losses could be made by means of hardware modifications.

The possibility of compensating for the greater losses of larger particles by sampling at anisokinetic conditions was then

investigated. If a nozzle larger than that required for isokinetic sampling at a given flow rate were used, then the larger particles would be oversampled with respect to the smaller ones. Theoretical calculations of the effect of oversampling large particles through anisokinetic sampling showed a potential for compensating for the system losses. The aspiration ratio, A, for anisokinetic sampling is given by Belyaev and Levin as[8]

$$A = 1 + \left(\frac{W}{v} - 1\right)\left(\frac{(2 + 0.62\ v/W)\ St_w}{1 + (2 + 0.62\ v/W)\ St_w}\right)$$

where W = duct velocity
v = velocity in sampling nozzle,
St_w = Stokes number of the nozzle, particle, duct velocity system,
$= \frac{\rho d^2 w}{18\ \eta\ D}$
ρ = particle density (=1.0 for aerodynamic diameters),
η = gas viscosity,
d = particle diameter, and
D = nozzle diameter.

Figure 4 also shows, as curve III, the product of the measured penetration, curve II, and the theoretical aspiration ratio (A) for W = 15 m/s, v = 4.65 m/s, and D = 0.794 cm. The potential for loss compensation is clearly evident.

Two sample runs were also made using 10-μm particles under the conditions for which curve III was calculated, with results shown in Figure 4: the measured values fell within ±10% of the theoretical predictions at this particle size.

Further verification of a revised sampling protocol which incorporated the anisokinetic compensation scheme was desired; however, a requirement for immediate use of the system in a field program halted further testing for a period of several months.

RESULTS OF SAMPLING CHARGED PARTICLES

The NEA dilution sampler was returned to Southern Research for further evaluation following modifications to the system and a period of field use. Most of the modifications were related to splitting the diluted flow so that simultaneous operation of two dichotomous samplers would be possible. The primary purposes of this second round of calibrations were (1) to determine whether the introduction of additional bends and a reduction in the diameter of the diluter piping following the flow split would cause significant losses and (2) to demonstrate that the two dichotomous samplers received similar samples. A secondary goal was to evaluate the effectiveness of the anisokinetic sampling

scheme suggested as a method for compensating for particle losses in the system upstream of the dichotomous sampler.

Initial tests of the modified system revealed increased losses in virtually every part of the system compared to those of the earlier tests. Very high losses were now found in the flexible hose which connects the diluter to the probe. Examination of the hose revealed that it had been overheated during a field sampling run, resulting in partial closure of the tubing and the creation of multitudinous fingerlike projections into the gas stream. At this point work was suspended until a duplicate hose could be obtained from the manufacturer.

After replacing the hose, subsequent runs produced data that showed losses that were less than those found with the damaged hose but still much higher than those measured in the original evaluation. Figure 5 illustrates the data taken with the modified system. Increased losses were found in the probe, hose, and diluter, including the front end of the diluter and the first bend. Except for the replacement of the damaged hose, it was presumed that none of these components had been modified since the earlier laboratory testing. Electrostatic effects were suspected, since the greatest increases in the losses occurred in the non-conducting PVC and Teflon portions of the train and did not seem to be related to inertial deposition in bends.

The data from calibration trials at a number of particle sizes are summarized in Table 4. Particle deposition as a percentage of the material reaching the component is plotted for the probe and hose in Figure 5. Table 4 includes (1) the amounts of material collected by the various surfaces; (2) the amount retained by each part of the train, as a percentage of the amount arriving at it; (3) the efficiencies of the dichotomous samplers in sampling from the diluted streams; and (4) comparisons of the measured and theoretical biases resulting from anisokinetic sampling. Larger anisokinetic biases were intended but were not obtained because the actual flows used were higher than intended, as discussed below. The dichotomous samplers were found to obtain practically identical samples at near 100% efficiency in sampling the diluted stream.

At this time the diluter was returned to NEA because it was needed for a field program which they had scheduled. The replacement hose was retained and a substitute probe was fashioned from a length of stainless steel tubing of the same internal diameter as that of the NEA probe. A series of experiments was then carried out to look into the possibility of electrostatic effects causing the increased loss compared to the first series of tests.

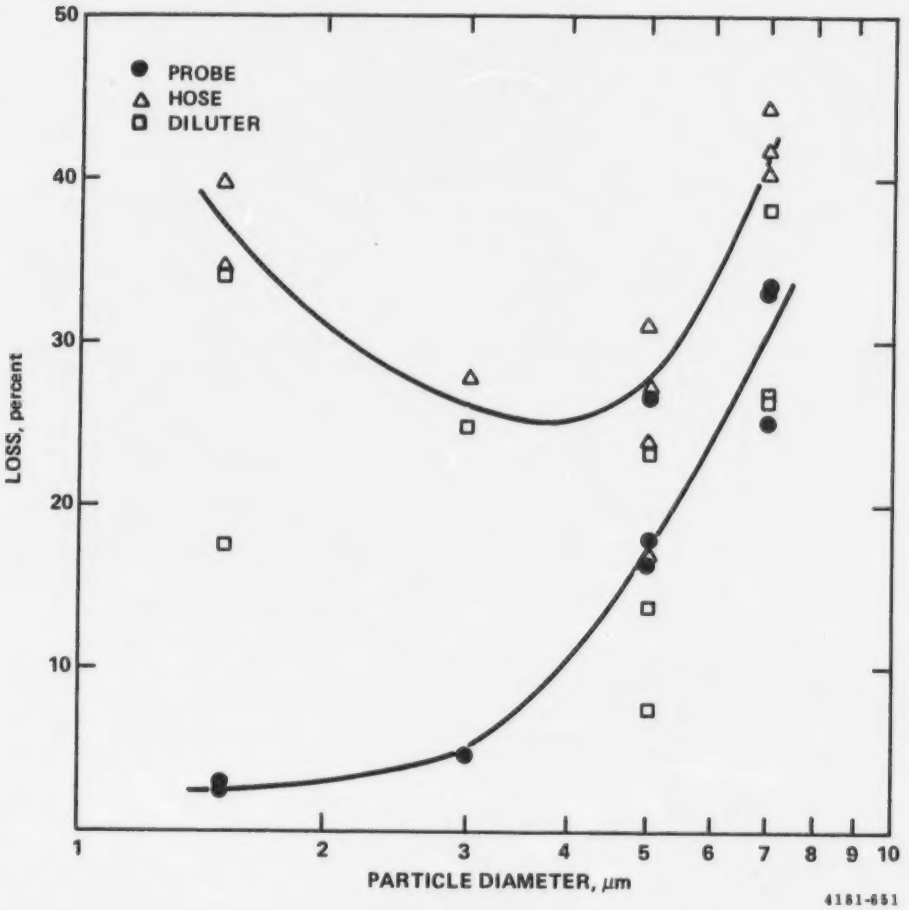

Figure 5. Probe, hose, and diluter losses by particle size for modified dilution system. Charged particles at ~ 33 lpm sampling rate.

Table 4. NEA Dilution System Performance With Charged Aerosol (second Test Series)

Test	Particle Diameter, μm	Precollector Catch,[a] (% Loss[b])	Probe Catch,[a] (% Loss[b])	Hose Catch,[a] (% Loss[b])	Diluter Catch,[a] (% Loss[b])	Left Dichotomous Catch,[a] (% Theory)	Right Dichotomous Catch,[a] (% Theory)	Filter Catch,[a] (% Penetration)	Total Catch[b]	Probe-Pitot Pressure Differential, in. w.c.	Run Time, min	Nominal Flow Rate, lpm	Probable Flow Rate, lpm	Concentration[d]	Concentration Ratio: Measured/ Theory
2REF									1750000			12.70		4176	
2NEA[c]	7	96000	440000	950000	1696954	5616	4065	837062	4029697	0.2	33	14.00	~14.00	~8722	~2.09
		(2.38%)	(11.19%)	(27.19%)	(66.71%)	(75.97%)	(55.36%)	(20.77%)							
3REF									1700000			12.70		3523	
3NEA[c]	7	2767500	770000	1650000	406475	28545	9410	960000	6591930	0.2	38	14.00	~14.00	~12391	~3.52
		(41.98%)	(20.13%)	(54.02%)	(28.94%)	(327.65%)	(111.19%)	(14.56%)							
4REF									4343750			12.70		5700	
4NEA[c]	7	3675000	1150000	810000	496950			1570125	7702075	0.2	60	14.00	~14.00	~9169	~1.61
		(47.71%)	(28.56%)	(28.15%)	(24.04%)			(20.39%)							
5REF									2137500			12.70		3740	
5NEA[c]	7	3240500	864000	1912500	54917			437360	6509277	0.23	45	16.10	~16.00	~9041	~2.42
		(49.78%)	(26.43%)	(79.53%)	(11.16%)			(6.72%)							
6REF									2813000			12.70		3692	
6NEA	7	5765000	1625000	1470000	483329	15950	25990	1304812	1.069E7	0.13	60	9.10	26.61	6697	1.81
		(53.93%)	(32.99%)	(44.54%)	(26.41%)	(40.70%)	(67.11%)	(12.21%)							1.69
7REF									3562500			11.80		5032	
7NEA	7	5195000	1086750	1300000	511575	30415	36700	1339025	9499465	0.2	60	14.00	33.00	4798	0.95
		(54.69%)	(25.25%)	(40.40%)	(26.68%)	(74.33%)	(91.67%)	(14.10%)							1.27
8REF									3550000			11.80		5014	
8NEA	7	7500000	2062500	1725000	916192	41410	33750	1407800	1.369E7	0.2	60	14.00	33.00	6912	1.38
		(54.80%)	(33.34%)	(41.83%)	(38.19%)	(95.96%)	(80.45%)	(10.29%)							1.27

(Cont'd.)

Table 4. (Continued)

Test	Particle Diameter, μm	Precollector Catch,[a] ($ Loss[b])	Probe Catch,[a] ($ Loss[b])	Hose Catch,[a] ($ Loss[b])	Diluter Catch,[a] ($ Loss[b])	Left Dichotomous Catch,[a] ($ Theory)	Right Dichotomous Catch,[a] ($ Theory)	Filter Catch,[a] ($ Penetration)	Total Catch[b]	Probe-Pitot Pressure Differential, in. w.c.	Run Time, min	Nominal Flow Rate, lpm	Probable Flow Rate, lpm	Concentration[d]	Concentration Ratio: Measured/ Theory
9REF									1470000			11.80		2076	
9NEA	5	1675000 (38.81$)	4275000 (16.19$)	530000 (23.94$)	124660 (7.40$)	38240 (128.42$)	44450 (100.44$)	1476360 (34.21$)	4316210	0.2	60	14.00	33.00	2180	1.05
															1.17
10REF									1395000			11.80		1970	
10NEA	5	2206000 (43.89$)	750000 (26.60$)	560000 (27.05$)	261123 (17.30$)	30750 (84.63$)	33400 (94.25$)	1184400 (25.57$)	5025673	0.2	60	14.00	33.00	2538	1.29
															1.17
11REF									1540000			11.80		2175	
11NEA	5	1373950 (30.92$)	551000 (17.95$)	780000 (30.97$)	239591 (15.78$)	37425 (85.78$)	36937 (86.83$)	1424925 (32.07$)	4443828	0.1	60	7.00	23.33	3174	1.46
															1.65
12REF									1007500			11.80		1423	
12NEA	5	1570000 (44.64$)	563550 (28.95$)	560000 (40.48$)	190180 (23.10$)	20150 (109.35$)	20254 (113.53$)	592825 (16.86$)	3516959	0.4	60	28.00	46.67	1256	0.88
															0.91
13REF									590000			11.80		486	
13NEA	3	140500 (11.31$)	52500 (4.77$)	292500 (27.88$)	187257 (24.75$)	15400 (92.96$)	15750 (97.71$)	538168 (43.33$)	1242055	0.2	68	14.00	33.00	554	1.14
															1.08
14REF									115900			11.80		123	
14NEA	1.5	64278 (17.11$)	7950 (2.55$)	120833 (39.81$)	62285 (34.10$)	4553 (129.98$)	3550 (105.33$)	112274 (29.88$)	375724	0.2	80	14.00	33.00	142	1.16
															1.02
15REF									99375			11.80		120	
15NEA	1.5	33975 (8.34$)	10450 (2.80$)	125000 (34.46$)	41934 (17.64$)	4214 (73.94$)	3884 (69.65$)	187750 (46.11$)	407207	0.2	70	14.00	33.00	176	1.47
															1.02

[a]Arbitrary units.
[b]Based on amount of aerosol penetrating to this part of the system.
[c]Damaged hose.
[d]Based on probable flow rate.

Measurements of the net charge/mass ratio showed that the particles carried a high unipolar charge at the inlet to the sampler while those which exited the hose carried no detectable net charge. A series of paired runs was then made in which a polonium-210 charge neutralizer was mounted on the probe inlet nozzle alternating with runs without the neutralizer. For comparison with the first test series data, all runs were performed at 14 lpm sample flow. The results of these tests are given in Table 5. Losses by particle size for the probe and hose, with and without charge neutralization, are shown in Figure 6. In comparing Figures 3 and 6, it is apparent that the differences in losses between the first evaluation and the second must indeed have been the result of electrostatic effects. The losses measured in the tests made with the charge neutralizer (Figure 6) agree with the results from the tests of the original, unmodified diluter (Figure 3).

The severe charge effects in the second test series were found to have been caused by the failure of a krypton-85 charge neutralizer which is an integral part of the aerosol generator. Evidently the tube containing the krypton gas developed a leak in the time between the two tests, resulting in the production of a highly charged aerosol by the generator during the second test series. In addition, the original evaluation was carried out in June when the air in the laboratory was relatively moist while the second test series was done in November when the air was drier. The lower humidity may have also played a role in the charge effects.

FLOW MEASUREMENT

The tests conducted with the diluter in the second round of calibrations were all carried out with the same mechanical setup and under the same operating conditions as in the previous tests with the exception of the diluter modifications. The pitot-to-diluter pressure differential was set at the same value used in the previous tests in order to presumably reproduce the sampling flow rate that had been used in the earlier calibrations. The sampling nozzle was selected to produce an anisokinetic sampling condition which would theoretically result in over-sampling large particles by approximately the amounts required to make up for the anticipated losses in the precollector, probe, and hose (approximately 2.5X at 10 μm). A reference isokinetic sampler was operated in parallel to provide true particle concentrations.

The results of the tests revealed that the theoretical and measured sampling biases did not agree well, contrary to previous experience. Further, too large a fraction of the particles entering the nozzle was retained by the precollector. The measured precollector efficiencies fell in line with what would have been expected for flow rates about twice those at which the

Table 5. Hose and Probe Losses With Charged and Uncharged Particles[a]

Test	Particle Diameter, μm	Precollector Catch[b] (% Loss[c])	Probe Catch,[b] (% Loss[c])	Hose Catch,[b] (% Loss[c])	Filter Catch,[b] (% Penetration)	Total Catch[b]	Run Time, min
16	5	139860 (30.91%)	28600 (9.15%)	117500 (41.37%)	166500 (36.80%)	452460	~20
17	5	135000 (19.14%)	54375 (9.54%)	228384 (44.27%)	287500 (40.77%)	705259	38
18	5	161250 (33.70%)	61000 (19.23%)	93757 (36.59%)	162500 (33.96%)	478507	~30
19	5	77500 (19.95%)	38000 (12.22%)	110383 (40.45%)	162500 (41.84%)	388383	30
20[d]	5	177500 (13.42%)	125000 (10.91%)	130345 (12.77%)	890000 (67.28%)	1322845	50
21	5	55000 (30.54%)	31500 (25.19%)	31069 (33.20%)	62500 (34.71%)	180069	30
22[d]	5	34000 (8.13%)	37500 (9.76%)	39238 (11.32%)	307500 (73.52%)	418238	30
23[d]	5	105000 (21.35%)	48000 (12.41%)	43725 (12.91%)	295000 (59.99%)	491725	30
24[d]	2	4160 (4.69%)	4080 (4.83%)	2388 (2.97%)	78000 (88.01%)	88628	40
25	2	15330 (7.44%)	1820 (0.95%)	56836 (30.10%)	132000 (64.08%)	205986	60
26[d]	7	504000 (34.40%)	162500 (16.91%)	142280 (17.82%)	656250 (44.79%)	1465030	30
27	7	258000 (36.66%)	51333 (11.51%)	152525 (38.66%)	242000 (34.38%)	703858	~15

[a]All tests were performed at 14 lpm with abbreviated sampling train consisting of precollector, probe, hose, and filter.
[b]Arbitrary units.
[c]Based on amount of material penetrating to this part of the system.
[d]A charge neutralizer was applied.

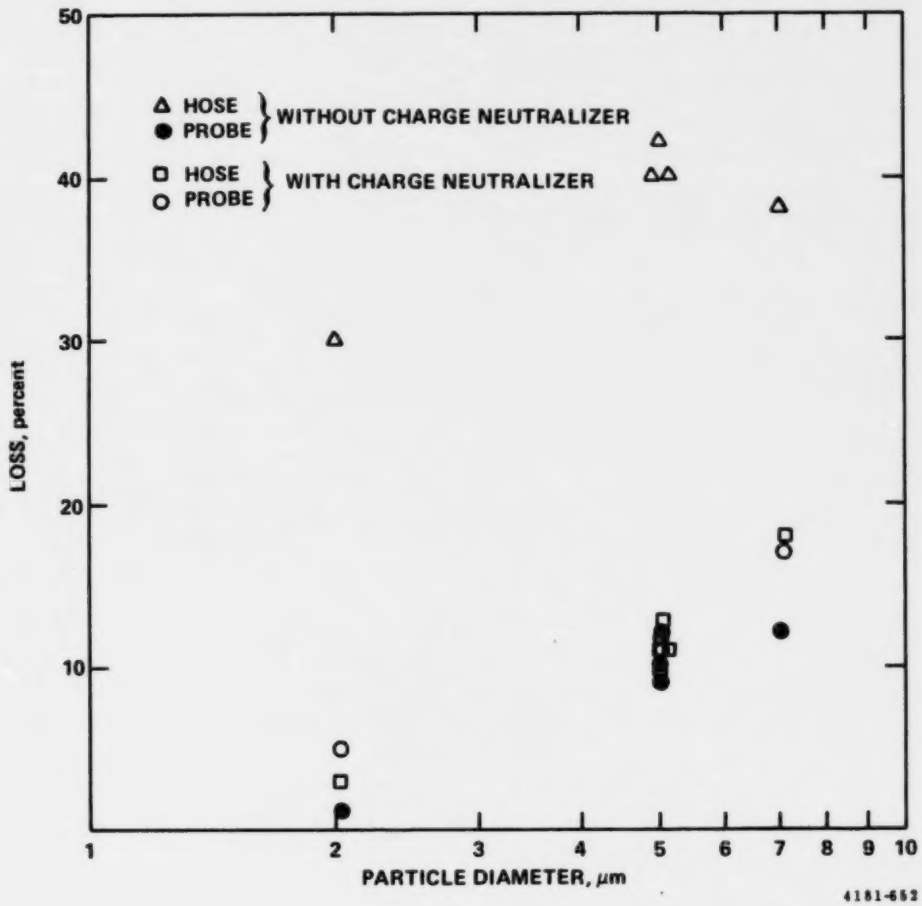

Figure 6. Probe and hose losses by particle size for charged and neutralized particles at a sampling rate of 14 lpm.

system had been set up to run (approximately 33 lpm versus 14 lpm). If the higher flows indicated by the precollector performance were used in calculating concentrations, the discrepancies between the measured and predicted sampling biases largely vanished. Subsequent conversations with NEA representatives revealed that the fittings used in attaching the hose to the probe and diluter had been changed in order to eliminate some minor flow restrictions. The elimination of the restrictions would have the effect of causing an increase in flow for any given probe/hose pressure drop. Attempts were made to measure the flow-pressure drop characteristics of the system; however, perturbations introduced by the available calibration devices interfered too much to make the data meaningful. The operating pressure differential between the probe tip and the diluter is only 2 to 5 mm of water. The previous flow calibrations were made using a venturi-based mass flow meter belonging to NEA which was assumed to produce no permanent pressure drop. Thus in the tests with neutral particles, the actual flows may have differed somewhat from the nominal values quoted as a result of similar, but probably smaller, errors in setting the sampling rates.

The samples obtained by the two dichotomous samplers in the modified unit were found to be reasonably similar and to fairly represent the concentrations of particles in the diluted stream. A few samples were taken of redispersed flyash in a simulated field environment using a larger wind tunnel than that used in performing the calibrations. In these runs it was noted that the particles in the larger (2-10 μm) size fraction did not adhere at all well to the membrane filter. Any slight jostling of the filters or breezes passing over them could cause much of the sample to be lost. Thus special provisions may be necessary for handling the coarse fraction filters when aerosols similar to this are sampled.

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